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INTERMEDIATE PULSEWIDTH LASER SYSTEM

Semiannual Technical Report No. 4

1 October 1967 - 31 March 1968

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This report is the fourth in the series of semiannual technical reports on Contract N00014-66-C-0056. Studies of the generators are continued. System performance with a preamplifier is considered as is the system stability. Polarization experiments were performed and damage thresholds for the various optical components were determined. Finally modifications to the laser system required as result of the above studies are described.

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ABSTRACT

This report is the fourth in the series of semiannual technical reports on Contract N00014-66-C-005. Studies of the generators are continued. System performance with a preamplifier is considered as is the system stability. Polarization experiments were performed and damage thresholds for the various optical components were determined. Finally, modifications to the laser system required as result of the above studies are described.

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Semiannual Technical Report No. 4

Intermediate Pulsewidth Laser System

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1. INTRODUCTION

The purpose of this program is to design and construct a glass laser system capable of providing high energy spike-free output in square pulses of 1, 3, 10, 30 and 100 microsecond lengths. The output beamspread is to be two milliradians or less.

The contract work was split into two phases. Phase one was to study feasibility of such a system, and was reported in Semiannual Technical Report No. 1. Phase two is to design, construct and deliver a system based on the findings in phase one.

The design of the system was discussed in Semiannual Technical Report No. 1. The principle of operation is to provide amplified spontaneous emission with a generator rod or rods. This emission is smooth in output, i.e., spike-free, and typically under high gain conditions, has a duration of 250-300 microseconds full width at half height. At the peak generator output a Kerr cell is switched to provide a square pulse of amplified spontaneous emission. The Kerr cell output is then fed into a preamplifier to further increase signal intensity to drive the final amplifiers. The total output from the combined final amplifiers is to be 1000 joules. If pulse sharpening occurs, the ramp generator can be employed to offset this pulse deformation and provide a square wave output pulse.

The system beamspread is controlled by the overall length of the system and the use of afocal telescopes. The diameter of the final amplifier divided by the overall length of the system is the aspect ratio. This determines the minimum beam divergence that can be obtained without the use of afocal telescopes. Because the rods used in the generator section have a smaller diameter than the preamplifier, an afocal telescope will be used to expand the beam from the generator to match the preamplifier cross section. This reduction of beam divergence will also help

to overcome a degradation of beamspread due to thermal distortion in the preamplifier. A second afocal telescope used between the preamplifier and the final amplifiers will help in further reduction of the beam divergence as well as provide an expanded beam diameter. This expanded beam will be large enough in diameter to allow the final amplifier to be clustered within the beam profile and thus make maximum use of the preamplifier output.

2. GENERATOR SECTION

In Semiannual Technical Report No. 3, it was reported that an output of 7 joules in one microsecond with 3 dB of pulse sharpening was obtained. Since that report the ramp function was introduced to one of the Kerr cells and the pulse sharpening was overcome to produce a square waveform pulse of one microsecond duration and an output of 7.2 joules. At this level of operation damage occurred on an enhanced gold reflector that was used to deviate the beam 90°. Some damage also occurred to the third generator rod. The laser rod was replaced and a 90° deviation prism was designed and constructed to eliminate the gold coated mirror. The prism was made of Schott SF-4 glass and the entrance and exit faces were low reflection coated with MgF_2. The roof angle was 86° to prevent feedback. At the time the prism was installed, a second capping shutter (Kerr cell) was also installed as well as a 3X afocal telescope. The purpose of the capping shutter was to decouple the preamplifier and final amplifiers when they were completed and scheduled for installation. The afocal telescope expanded the beam to fill a 3 cm diameter preamplifier. The addition of these elements results in a factor of 6 reduction in throughput.

To overcome the deficiency, considerably more than 10 J/cm² must be delivered by the third generator rod. The output was gradually increased to 17.8 J in 0.8 μs. This was 22.6 J/cm². At this level the prism was damaged internally and also on the surface of the reflecting face. The laser rod was also damaged and another laser rod with a different composition and produced in such a way as to have low platinum content was substituted.

The laser glass was double doped containing 2 wt% Nd_2O_3 and 3 wt% of Yb_2O_3. Doping the laser glass with Yb_2O_3 increases the energy storage capability of the glass because the specific gain coefficient is reduced by a factor of four as explained in Semiannual Technical Report No. 1. Also, if a high enough gain

can be achieved there would not be any pulse sharpening due to the generator section. The rod was 15 mm in diameter because it was a convenient size to fit the existing laser rod fixture and also because the cross-sectional area was increased by a factor of 2.25 over the previous generator rod. This, in turn, reduced the energy density at the output end and hence reduced the possibility of damage.

Gain measurements were performed on this rod with a maximum pump energy input to two lamps of 24 kilojoules. At this input a gain of 15.7 dB was measured with a 2 ms pump pulse. The gain versus pump input is plotted in Figure 1.

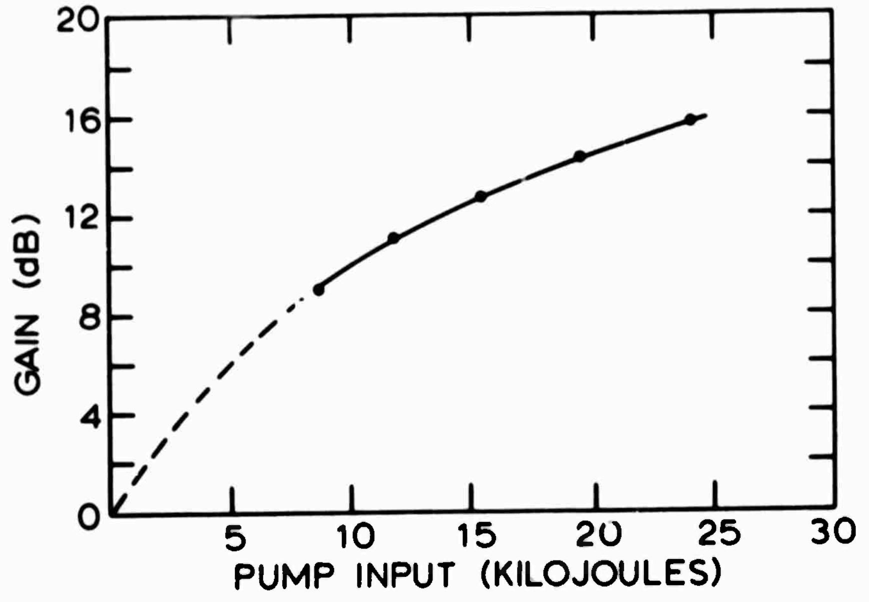

Figure 1. Small signal gain of double doped generater rod as a function of ramp input. Pump duration 2 ms, pumped length 85 cm.

The gain level obtained was too low to provide the necessary energy out of the generator section. The possibility existed that the gain at 1.06 μm was held down by fluorescent emission at 1.015 μm since there is a fluorescent emission peak at this wavelength for the Yb^{3+} ion in the laser glass.[1] At room temperature the gain at 1.015 μm is offset by the lower population

in the terminal state for the 1.06 μm emission and therefore the gain at 1.015 μm was probably not a problem. However, to be absolutely certain, the spontaneous emission at 1.015 μm and 1.06 μm was monitored as a function of pump input. What one would look for is a rapid rise in the 1.015 μm emission versus pump input compared to that of 1.06 μm emission. At a pump input of 8.65 kilojoules the relative signals measured were 0.11 volts and 3.8 volts respectively, at 1.015 μm and 1.06 μm. At 24 kilojoules pump input the signal levels were 0.27 volts and 15 volts, respectively at 1.015 μm and 1.06 μm. This was an increase of 3 dB at 1.015 μm and about 6 dB increase at 1.06 μm. This was a good indication that the gain at 1.015 μm was not saturating the gain at 1.06 μm.

Another 15 mm diameter generator rod was fabricated from single doped 3 wt% Nd_2O_3. The gain versus pump input is shown in Figure 2.

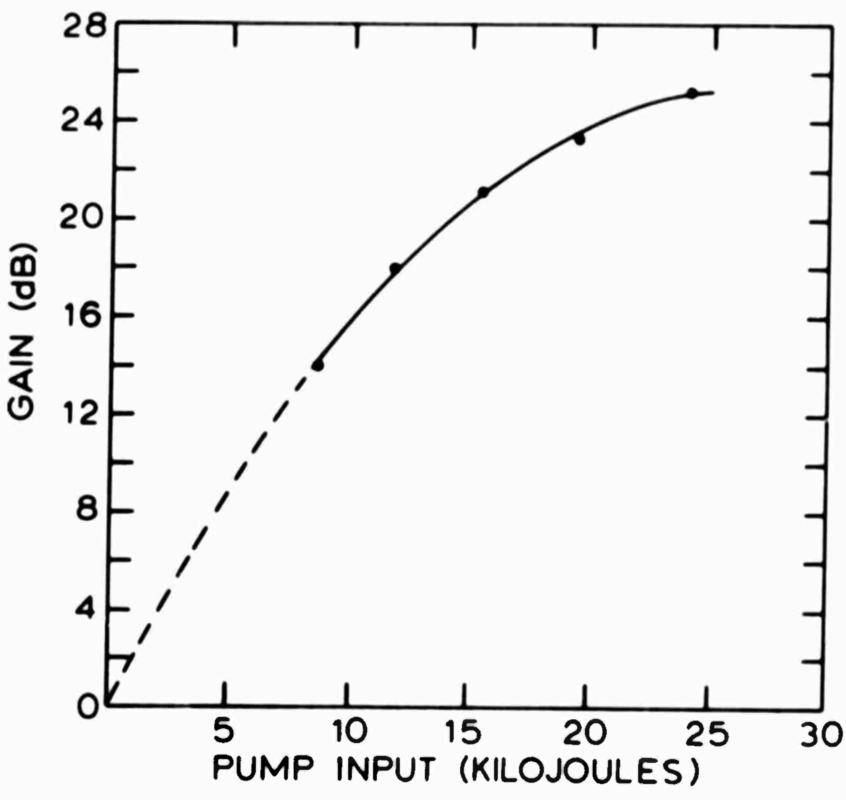

Figure 2. Small signal gain of generator rod with 3 wt% Nd_2O_3 as a function of pump input. Pump duration 2 ms, pumped length 85 cm.

The maximum gain was 25.2 dB at a pump input of 24 kilojoules. It was expected that this glass would be more durable because it was made in an all ceramic environment. With this rod an output of 2.4 joules was obtained in a 1 μs pulse at a gain level of 21 dB. At maximum gain (25 dB) the energy delivered by the generator section was 7.25 joules. The beam divergence was 2.5 mr full angle at the half energy point.

2.1 WRAP DARKENING

The gain in the 3 wt% doped rod was lower than in the original rod and this made it necessary to pump the other two generator rods at maximum gain. When this was done, the output energy gradually decreased when a number of shots were taken. An investigation of this problem was initiated to determine the reason for this behavior which turned out to be caused by darkening of the wraps used to couple the flashlamps to the laser rods.

The flashlamps for the generator rod are coupled to the laser material by a close wrap reflector housing. This simply means a reflective material is wrapped around the lamps and is in contact with the flashlamp envelope with the laser rod between the lamps. The reflectors are sheet brass with the proper radius of curvature to fit the OD of the lamps. The brass is buffed to a high lustre, electroplated with silver and buffed again. After the lamps were fired a number of times, the output dropped off because the silver began to darken - a phenomenon we call solarization. Even though the darkening is not readily apparent upon visual inspection, a thorough cleaning of the wraps restores the laser output. When the discoloration was very evident, it was found that the gain in the generator rods could be 7 dB lower than normal. The situation was critical because a very time consuming maintenance problem was involved.

Previous work with other laser systems using General Electric Company lamps indicated that wrap darkening should not be a problem. The lamps that were used on this device were obtained from PEK Labs., Inc. A General Electric and a PEK lamp were triggered with a high voltage source such as a Tesla coil. The lamps were positioned in front of the entrance slit to a spectrograph. The spectra from each lamp was recorded. The presence of mercury was recorded with a PEK lamp but not for a GE lamp. The presence of mercury raised the question of absorption by the silver in the region 2000 - 31000 angstroms. In this

region the silver reflectance is not likely to be more than 0.30. Also in this region, at 2537 angstroms, there is a strong mercury resonance line that could produce a photochemical reaction with the silver and might even produce oxidation. A large supply of these lamps were on hand for the system and so it was not possible to use another manufacturer's lamps.

The only alternative was to filter out the ultraviolet radiation. This was done by enclosing the lamps in Pyrex sleeves. Pyrex tubing was available with either a 32 mm OD or a 30 mm OD that fit over the lamps. Test shots were made with both sizes of tubing. The wraps did not darken with either tubing size. Use of the tubing resulted in a drop in gain at a given input. The 32 mm OD tubing lowered the gain 4.5 dB whereas the 30 mm OD tubing lowered the gain 3 dB. On this basis, the smaller tubing size was chosen for use in the system. The drop in gain was not serious because it could be made up by increasing the flashlamp input energy.

3. SYSTEM PERFORMANCE WITH A PREAMPLIFIER

A double-doped laser glass containing 2.5 wt% Nd_2O_3 and 4 wt% Yb_2O_3 was chosen for the preamplifier and final amplifiers. The reasons for choosing double-doped laser glass were discussed in Semiannual Technical Report No. 1. The particular values of doping concentration were chosen to minimize non-uniform gain distribution across the 3 cm diameter rod. This glass becomes somewhat like three level laser material in that unpumped regions exhibit a higher loss coefficient than do the pumped regions. Because of this, a laser rod fixture should be designed that will minimize the length of laser rod that is not pumped. In order to do this, both entrance and exit windows have to be provided. The windows were made of low loss laser glass doped with Nd_2O_3. The windows and laser rod were Brewster ended and mounted in the low-loss plane for the linearly polarized laser emission from the generator section. Provisions were provided in the fixturing to permit rotational adjustments of the windows with respect to the laser rod and thus achieve parallelism between the rod ends and the windows.

At this time the gain and the gain uniformity were unknown for a 3 cm x 1 meter rod. The rod was pumped with four lamps each a meter long in a close-wrap pump configuration. A 2 ms pulse duration was used and the maximum input was 12 kilojoules per lamp for a total of 48 kilojoules.

Past experience indicated that the maximum gain per kilojoule could be obtained with this pump pulse duration. The gain versus pump input plot is in Figure 3, and shows a maximum gain of 14 dB at 48 kilojoules pump input.

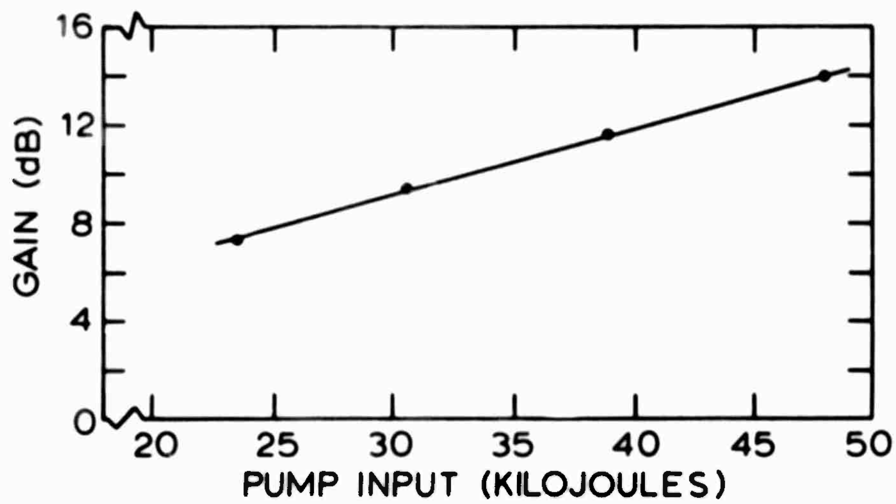

Figure 3. Small signal gain of 3 cm diameter double-doped preamplifier with doping concentrations 2.5 wt% Nd_2O_3 and 4 wt% Yb_2O_3. Pump duration 2 ms, pumped length 85 cm.

The gain profile was measured and it was determined that the periphery of the rod had 30 - 40% more gain than the center of the rod. This was undesirable because excessively high energy density near the surface of the rod could produce damage to the laser glass. Based on these measurements, it was decided to fabricate a new preamplifier and a set of final amplifier rods with doping levels of 2 wt% Nd_2O_3 and 3 wt% Yb_2O_3, a compromise between obtaining sufficient gain and obtaining better gain uniformity. Since it will require several months to fabricate the new rods, further discussion and experiments are restricted to the present preamplifier.

During this report period the system consisted of a generator section coupled to a preamplifier. Due to power supply limitations, the maximum gain in the preamplifier was limited to 14 dB. The maximum energy output in a one microsecond pulse was 23 joules. The ramp function on one of the Kerr cells was applied to maintain a square wave form.

A completely separate 108 kilojoule power supply was integrated into the laser system in an effort to obtain higher gain in the preamplifier. The preamplifier gain versus pump input is plotted in Figure 4. A maximum gain of 16.75 dB was obtained at a pump input of 108 kilojoules. At a pump input of 78 kilojoules, a gain of 14 dB was realized. This was the same gain as obtained earlier with 48 kilojoules input with the power supply normally used. The discrepancy was accounted for by making a study of the power supply characteristics.

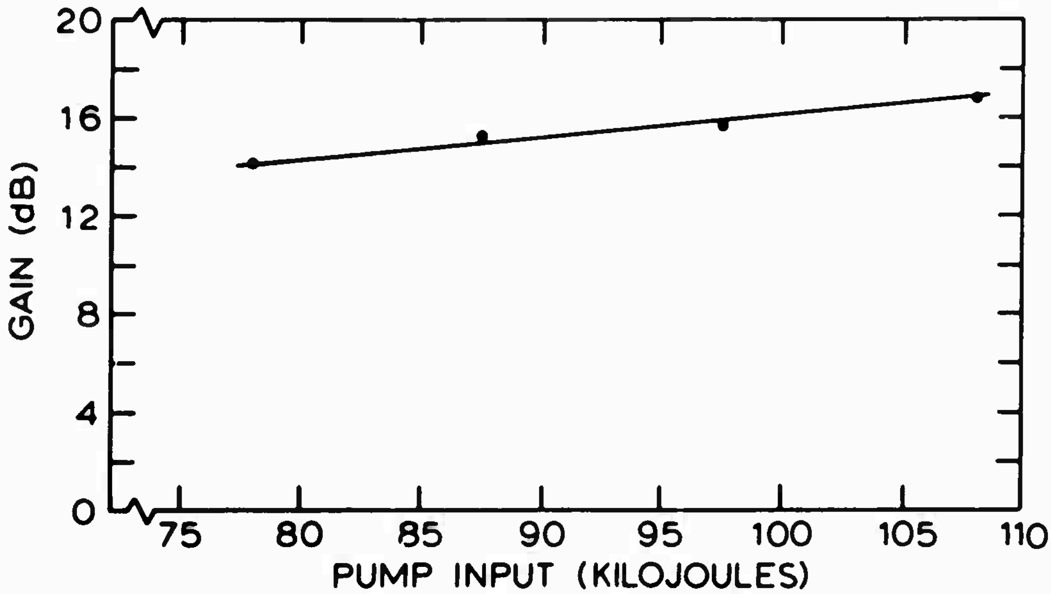

Figure 4. Small signal gain of 3 cm double-doped preamplifier with a doping concentration of 2.5 wt% Nd_2O_3 and 4 wt% Yb_2O_3, using 108 kJ power supply. Pump duration 3 ms, pumper length 85 cm.

The power supply normally used provided 48 kilojoules in a 2 ms pulse duration. This was broken down to 12 kilojoules for each of the four flashlamps. Simultaneous traces were recorded with a dual gun CRT of the flashlamp pulse and the spontaneous emission from the preamplifier. Peak gain occurs at the time the amplified spontaneous emission is at a peak. Any flashlamp output that occurs after the peak in spontaneous emission does not contribute to peak gain. The total area under the trace obtained for the flashlamp was measured. Also, the area up to the time of peak gain was also measured. The ratio

of the two areas is a measure of the useful pump input. For this power supply, 85 percent of the total flashlamp output occurred before the peak gain was reached in the preamplifier.

With the 108 kilojoule power supply, the maximum energy per lamp was 27 kilojoules in a 3.3 ms pulse duration and at lower inputs the flashlamp pulse decreased to 2.8 ms. The capacitance per lamp was 2160 mF. Even though the pulse duration was about one millisecond longer than for the power supply described above, of more significance was the fact that a very long tail was evident in the flashlamp traces obtained with the CRT. The area under the flashlamp traces was measured and a ratio as explained previously was obtained which indicated that 50 percent of the total flashlamp output occurred before the peak gain in the preamplifier.

Even though there is a gain deficiency with the 108 kilojoule power supply used on the preamplifier, an increase in gain was realized and therefore the system was operated with a 1 μs pulse width and 47.6 joules output was measured. At this output level several damage sites occurred around the periphery of the rod at the output end. Previous experiments were cited that this rod did not have gain uniformity. As a result of the higher gain along the surface of the rod, an excessive energy density could have been responsible for the occurrence of the damage sites. When the output energy was reduced slightly, the damage sites did not increase in size or number.

4. POLARIZATION EXPERIMENTS

The whole system is highly dependent upon linearly polarized 1.06 μm emission. Any depolarization in the third generator rod will produce a loss in output from the preamplifier because of the Brewster ended windows and also an insertion loss for the final Faraday rotator because a polarizer is required. Measurements were made on both the third generator rod and the preamplifier.

Depolarization effects produced by the third generator rod were measured for the pumped and unpumped cases. The 1.06 μm signal into the third generator rod is linearly polarized by virtue of having passed through a Faraday rotator with a Glan type double beamsplitting polarizer at the output end of the device. The polarization vector was in the low-loss plane for

the Brewster ended rods. The throughput was analyzed with another calcite polarizer and the signal was monitored with a photodetector. Measurements were made with the analyzer parallel to and then perpendicular to the low-loss plane for both the pumped and unpumped cases. When the rod was unpumped the ratio of the signals was 20.8 dB and when pumped it was 19.65 dB. Thus approximately one percent of the signal was in the undesired plane of polarization.

When the same measurements were performed on the pre-amplifier, the ratio was 5.85 dB and 5.45 dB respectively for the unpumped and pumped conditions. Approximately 22 percent of the energy appeared in the undesired plane of polarization and would be rejected by the input polarizer used with the final Faraday rotator.

5. SYSTEM STABILITY

The high gain in this system requires the elimination of all reflections from system elements. This was done primarily by tilting all the optical elements to prevent axial feedback. This method is not applicable to metal surfaces that reflect diffusely. To prevent diffuse reflections, a system of highly absorbing glass stops was installed. The edges of the stops exposed to the laser emission were beveled to simulate a knife edge and the plates were then adjusted to allow only paraxial emission to pass through.

As reported elsewhere, the original third generator rod was replaced by a rod of lower gain which made it mandatory to pump the final two generator rods to a maximum gain of 60 dB. Tests were initially performed with the Faraday rotators inactive to measure system stability and made appropriate adjustments to eliminate the reflections. A maximum gain of only 50 dB was permissible in the first two rods. At that gain level enough feedback occurred to produce oscillation in the system. A systematic check of all possible reflections led to the conclusion that the feedback was due to either scatter from the calcite used in the polarizers or to manipulate internal reflections in the polarizers. The effective reflectivity of some of the tilted polarizers was therefore -50 dB. However, when the Faraday rotators were energized the maximum gain of 60 dB per rod was realized.

This system including the preamplifier was used to obtain information with regard to damage thresholds in optical glass since no information was available in the 1 μs time domain. While this investigation was in progress, an appreciable amount of energy was detected being emitted in the backward direction by the third generator rod. The tests were conducted with the generator section coupled to the preamplifier and the output was passed through a one meter focal length lens. An antireflection coating of MgF_2 was used to suppress reflections from the double element lens. With the antireflection coating the reflectance per surface was 0.005. Careful measurements were made of the losses in the system from the input end of the third generator through the preamplifier. The gain in both of these rods had been measured. By monitoring the energy emitted in the backward direction from the input end of the third generator rod, it was possible to compute the effective reflectivity of the lens for various distances between the lens and the output end of the preamplifier.

It was determined that the lens was responsible for the feedback condition by placing attenuator plates between the lens and the preamplifier and measuring the decrease in signal resulting in the reverse direction. Measurements were then made with the lens 26 cm from the output window of the preamplifier. With an output of 13.5 joules in a one microsecond pulse, the energy measured in the backward direction emitted by the input end of the third generator rod was 6.2 joules. The effective reflectivity was calculated to be 1.11×10^{-3} or in terms of loss it was -29.5 dB. For a 50 cm spacing the effective reflectivity was 2.98×10^{-4} or -35.26 dB and for a 100 cm spacing it was 4.97×10^{-5} or -43 dB.

6. THRESHOLD FOR DAMAGE TO OPTICAL MATERIAL FOR A ONE MICROSECOND PULSE

The threshold energy density required to damage optical material with a one microsecond pulse was not known at this time. It was important to have this information in order to build a durable system.

During this time period a billet of double-doped glass with 2 wt% Nd_2O_3 and 3 wt% Yb_2O_3 became available from the all ceramic glass working facility at the American Optical Corporation. The billet was damage tested in a number of areas. Only one damage site was produced in this billet and this occurred at an energy density of 80 J/cm². This was 100 percent above the required

damage threshold. The damage site was cut out of the billet, and the remainder of the glass was used to fabricate a preamplifier rod.

A series of experiments were performed with a number of high optical quality materials that were considered candidates for elements in the system. The results are listed below:

(a) Corning 8463 high index flint glass was to be used as the active element in a Faraday rotator at the output end of the preamplifier. The threshold for damage was approximately 10 J/cm^2.

(b) Schott SFS-6 high flint glass could also be used as a Faraday rotator element. The threshold for damage was not measured but at 16 J/cm^2 severe damage resulted throughout the sample volume.

(c) Terbium-doped glass was used as the active element in the Faraday rotators in the generator section. Threshold for damage was about 16 J/cm^2. This was well above the energy density expected in that section of the system.

(d) Schott SF-4 glass was fabricated into stacked plate polarizers for use at the output end of the preamplifier. The damage threshold was 29 J/cm^2.

(e) Schott SF-6 glass was another candidate for a Faraday rotator element at the output end of the preamplfier. However, the Verdet constant for this glass is low (0.02 min. $Gauss^{-1} cm^{-1}$) which would require the use of two magnets in series to obtain sufficient backward attenuation without suffering an appreciable insertion loss. The damage threshold was 35 - 40 J/cm^2.

(f) Glan, double beamsplitting, calcite polarizers were also tested. Threshold for damage was not obtained as 75.7 J/cm^2 was put through the samples without damage.

The results indicate that some changes will have to be made in the selection of optical materials for this system. The changes will be discussed in the next section.

7. MODIFICATIONS TO THE LASER SYSTEM

The experiments and results discussed in the previous sections have led to a number of modifications to the system. The third generator rod will be replaced by an 18 mm diameter liquid-cooled rod doped with 2 wt% Nd_2O_3. A gain of 30 dB should be possible with an input of 24 kilojoules. The 18 mm rod will be stopped down at its input end to produce a 15 mm diameter beam at the output end and prevent surface damage to the rod. The low doping will permit uniform pumping.

A new eyepiece for the afocal telescope used to couple the generator section to the preamplifier will be designed to change the telescope from 3× to 2× magnification.

The results of the feedback experiments with the lens at the output end of the preamplifier indicate that a Faraday rotator should be added between the third generator rod and the preamplifier. This will be done when all the necessary parts are completed.

The doping concentration of the preamplifier and final amplifiers is being changed from 2.5 wt% Nd_2O_3 - 4 wt% Yb_2O_3 to 2 wt% Nd_2O_3 - 3 wt% Yb_2O_3 in an effort to obtain more uniform gain distribution over the rod diameter. This may limit the maximum gain attainable to some lower value than was anticipated. To overcome the possibility of not enough gain, a 50 cm long by 3.8 cm diameter rod will be added between the output end of the third generator rod and the preamplifier.

The damage threshold experiments indicate that the glass element used in the final Faraday rotator (Corning 8463 glass) will have to be changed. At the present time, no other suitable glass with a Verdet constant of 0.03 or higher at 1.06 μm is available. Therefore, experiments have started in our glass laboratory to make a glass with comparable Verdet constant and higher damage threshold. A glass other than Schott SF-4 is also required for the output collector lens. The glass laboratory will also work on this problem.

A schematic diagram of the modified system is included in Figure 5.

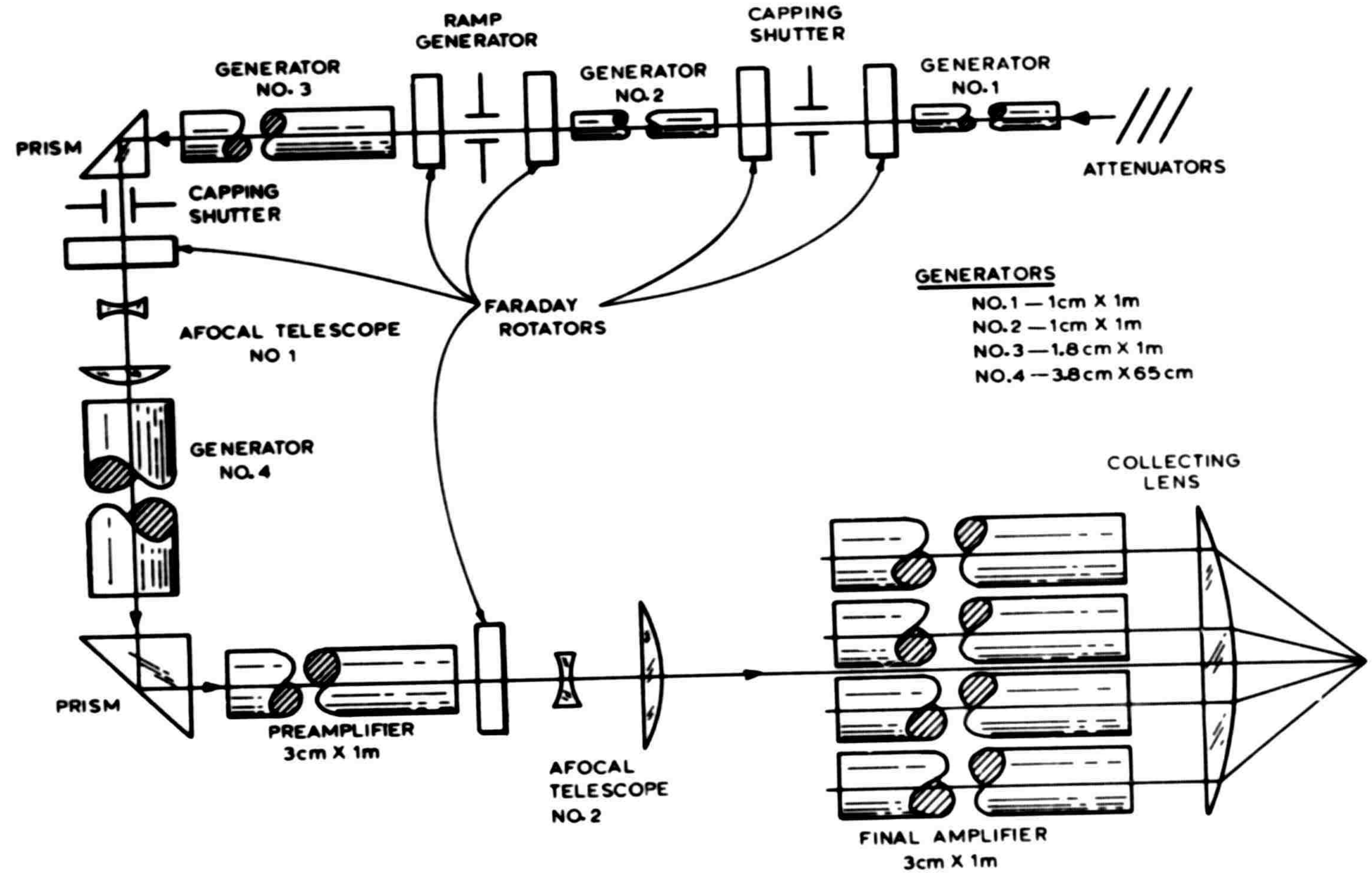

Figure 5. Schematic diagram of modified intermediate pulsewidth laser system.

REFERENCE

1. E. Snitzer, "Laser Emission at 1.06 μ from Nd^{3+} - Yb^{3+} Glass," IEEE Journal of Quantum Electronics, Vol. QE-2, September 1966, Page 562.